ABSTRACT

Sundaland, which covers Peninsular Malaysia, Sumatra, Java, Borneo, Thailand, Myanmar, Cambodia, Laos and Vietnam, has moved towards the east before the Aceh earthquake, but shortly after the earthquake, the motion of most of Sundaland was towards the west. The main objective of this study is to monitor the post-seismic motion of Peninsular Malaysia due to the previous earthquakes such as Aceh 2004, Nias 2005 and Bengkulu 2007. Seventy eight (78) Malaysia Real Time Kinematic Network (MyRTKnet) and thirty (30) Global Positioning System (GPS) stations worldwide were used in this study. The Bernese 5.0 software with double difference strategy was used to process all the data. The results show that the west-northwest part has the worse deformation in comparison to the other parts. Generally, from 2004 until 2005 Peninsular Malaysia moved towards west-southwest by 8.2 cm per year but in 2006, there was a slight change in the motion. From 2006 until 2008, the southern part has moved towards east-southeast by 0.23 cm per year and the northern part moved towards west-southwest by 5.9 cm per year. These motions have caused different displacements between both northern and southern parts, and may have triggered local faults movement. The other objective of this study is to identify whether the Raub-Bentong suture had any seismic activity. In 2007 until 2009, several tremors were recorded in Bukit Tinggi, Kuala Pilah, and Jerantut areas. These tremors are believed as indications of fault movement in Bukit Tinggi, Kuala Lumpur or Raub-Bentong. The determination of fault movement in this study was based on selected MyRTKnet baselines analysis. The technique is unable to identify the fault movement due to the fact that MyRTKnet stations are sparse and are far away from the fault lines. Therefore, it is necessary to carry out GPS field campaign along Bukit Tinggi and Kuala Lumpur faults in the future. Besides that, continuous post-seismic monitoring is needed to get a better picture of the seismic cycle in Peninsular Malaysia.

ABSTRAK

Sundaland yang meliputi Semenanjung Malaysia, Sumatra, Jawa, Kalimantan, Thailand, Myanmar, Kemboja, Laos dan Vietnam telah bergerak ke arah timur sebelum gempa bumi Aceh, tetapi tidak lama selepas gempa, pergerakan sebahagian besar daripada *Sundaland* adalah ke arah barat. Objektif utama kajian ini adalah untuk memantau pergerakan pasca-sesmik bagi Semenanjung Malaysia terhadap gempa bumi terdahulu iaitu Aceh 2004, Nias 2005 dan Bengkulu 2007. Tujuh puluh lapan (78) *Malaysia Real Time Kinematic Network (MyRTKnet)* dan tiga puluh (30) stesyen Sistem Penentuan Sejagat (GPS) bagi seluruh dunia digunakan dalam kajian ini. Perisian Bernese 5.0 dengan strategi perbezaan ganda dua telah digunakan untuk memproses semua data. Keputusan pemprosesan menunjukkan bahawa bahagian barat-barat laut Semenanjung Malaysia telah mengalami deformasi yang paling ketara berbanding dengan bahagian lain. Secara umum, dari tahun 2004 hingga 2005 Semenanjung Malaysia telah bergerak ke arah barat-barat daya sebanyak 8.2 cm setahun tetapi pada tahun 2006, terdapat sedikit perubahan dalam pergerakannya. Dari tahun 2006 hingga 2008, bahagian selatan telah bergerak ke arah timur-tenggara sebanyak 0.23 cm setahun dan bahagian utara telah bergerak ke arah barat-barat daya sebanyak 5.9 cm setahun. Gerakan ini telah menyebabkan anjakan berbeza di antara kedua-dua bahagian utara dan selatan, dan kemungkinan mencetuskan pergerakan sesar tempatan. Objektif lain kajian ini adalah untuk mengenalpasti samada *jahitan* Raub-Bentong mempunyai aktiviti sesmik. Pada tahun 2007 hingga 2009, beberapa gegaran telah direkodkan di kawasan Bukit Tinggi, Kuala Pilah, dan Jerantut. Gegaran ini dipercayai sebagai petanda gerakan sesar di Bukit Tinggi, Kuala Lumpur atau Raub-Bentong. Penentuan pergerakan sesar di dalam kajian ini adalah berdasarkan analisis garis dasar *MyRTKnet* yang terpilih. Teknik tersebut tidak boleh mengenalpasti pergerakan sesar disebabkan fakta yang menunjukkan stesyen *MyRTKnet* adalah jarang dan jauh daripada garisan sesar. Oleh yang demikian, ia adalah perlu untuk melaksanakan kempen kerjaluar GPS di sepanjang sesar Bukit Tinggi dan Kuala Lumpur pada masa hadapan. Selain itu, pemantauan pasca-sesmik secara berterusan diperlukan untuk mendapatkan gambaran putaran sesmik yang lebih baik di Semenanjung Malaysia.

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LIST OF ABBREVIATIONS

AS	:	Anti Spoofing
BPE	:	Bernese Processing Engine
CZH	:	Code Zero Header
CZO	:	Code Zero Observation
DGPS	:	Differential Global Positioning System
DGMM	:	Department Geoscience and Mineral Malaysia
DSMM	:	Department Survey and Mapping Malaysia
ESE	:	East-Southeast
GEODYSSEA	:	Geodynamic South and South East Asia
GLONASS	:	The Global Navigation Satellite System
GMT	:	Generic Mapping Tool
GNSS	:	Global Navigation Satellite System
GPS	:	Global Positioning System
IGS	:	International GNSS Services for Geodynamic
ITRF	:	International Terrestrial Reference Frame
MASS	:	Malaysia Active GPS System
MMD	:	Malaysia Meteorology Department
MMI	:	Modified Mercalli Intensity
MyRTKnet	:	Malaysia Real Time Kinematic GNSS Network
N	:	North
NAVSAT	:	Navy Navigation Satellite System
NAVSTAR	:	Navigation Satellite Timing and Ranging
NNW	:	North-Northwest
NW	:	Northwest
PPP	:	Precise Point Positioning

PZH	:	Phase Zero Header
PZO	:	Phase Zero Observation
QIF	:	Quasi Ionosphere Free
RINEX	:	Receiver Independent Exchange
RMS	:	Root Mean Square
S	:	South
SA	:	Selective Availability
SE	:	Southeast
SEAMERGES	:	South East Asia Mastering Environmental Research with Geodetic Space Technique
SSE	:	South-Southeast
USGS	:	United States Geological Survey
UTC	:	Universal Time Coordinate
VRS	:	Virtual Reference Station
WNW	:	West-Northwest

LIST OF SYMBOLS

a	-	Amplitude associated with the decay (mm)
A_o	-	A standard value as a function of distance
A_t	-	Maximum trace amplitude
b	-	Constant amplitude (mm)
ΔX_1; ΔX_2; ΔX_n	-	Co-seismic displacement (constant parameter)
M_L	-	Local magnitude
$Po_1(t)$; $Po_2(t)$; $Po_n(t)$; $Post(t)$	-	Post-seismic displacement
t	-	Time of any desire epoch
t_0	-	Time of reference epoch
u	-	Mean relative displacement
V	-	Velocity
$X(t)$	-	Position at time t
X_0	-	Position at time t_0

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CHAPTER 1

INTRODUCTION

1.1 Introduction

In the last few decades, geoscientists have used polar magnetic to explain plate movements; thereby making plate tectonic concepts acceptable by the geosciences community. The advent of the space technique in the 1970s has led to the development and global acceptance of the Global Positioning System (GPS) technology. This new technique has evolved into spatiality in the studying of geodynamics. In 1994 there was a project known as GEODYSSEA (Geodynamic South and South East Asia). The aim of this project was to study the plate motion and crustal deformation in the region of South and South East Asia (S.E.A). The result of that project showed that Sundaland block which covered Peninsular Malaysia, Sumatra, Java, Borneo, Thailand, Myanmar, Cambodia, Laos and Vietnam has a distinct relative motion with respect to the stable part of the Eurasian Plate (Simon *et al.*, 1999).

Few years after GEODYSSEA was completed, there were two big earthquakes, which devastated the Sundaland block. The first one occurred near the Aceh region, North of Sumatra with the epicenter 3.316^{o}N, 95.845^{o}E and depth about 30 kilometers with 9.1 Mw (USGS, 2004) on 26 December 2004. The second earthquake occurred with the epicenter 2.074^{0}N, 97.013^{o}E and depth about 30 kilometers with 8.6 Mw (USGS, 2005) hit the Nias region, North of Sumatra on 28 March, 2005. The first earthquake caused a deformation of an area over 4000 kilometers from the epicenter.

The largest co-seismic displacement reached to about 400 kilometers away from the epicenter (Vigny *et al*., 2005). The Nias earthquake also caused deformation but was not as widespread as the first Aceh earthquake. Kee *et al*. (2005) observed that, the shape of Peninsular Malaysia has deformed into an irregular form. However, this occurrence may vary from time to time and it could become an interesting issue for future investigation.

1.2 Problem Statement

Although Peninsular Malaysia is located in the relative stable continent, but according to a tectonic model by Metcalfe (2006) it shows that Peninsular Malaysia is divided into two tectonic blocks (Figure 1.1). Peninsular Malaysia consists of several inactive major faults such as Bukit Tinggi Fault, Bok Bak Fault, Kuala Lumpur Fault, Lebir Fault, Lepar Fault, and Mersing Fault (Figure 1.2) (DGMM, 2008). When the big earthquake in December 2004 occurred, Peninsular Malaysia was deformed into an irregular form. After the Aceh earthquake, there were several earthquakes also occurred in the west coast Sumatra in 2005 (Nias) and 2007 (Bengkulu), which caused Peninsular Malaysia experiencing a complex post-seismic. Because of the complexity of the post-seismic, a continuous monitoring is needed to investigate the impact of those earthquakes in Peninsular Malaysia from 2004 until 2008. In the meantime, there were several tremors recorded in Bukit Tinggi, Kuala Pilah and Jerantut areas from 2007 until 2009. Those tremors are believed as early indication of fault reactivation in Peninsular Malaysia. The other indication of fault reactivation also can come from the post-seismic pattern of Peninsular Malaysia. Therefore, it is necessary to investigate whether there is any seismic activity in the suspected fault due to the Aceh, Nias and Bengkulu earthquakes.

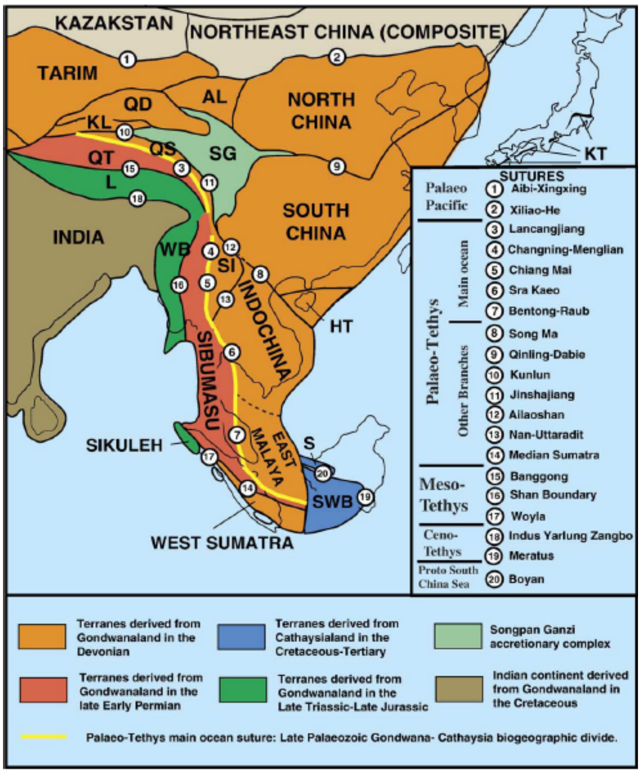

Figure 1.1 Geological model of East and Southeast Asia (Metcalfe, 2006)

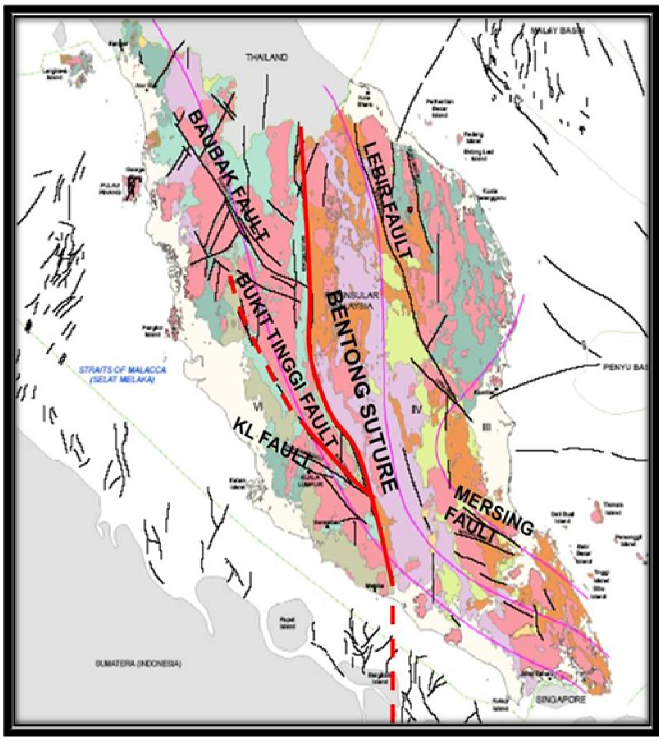

Figure 1.2 Distribution of Major Fault in Peninsular Malaysia (DGMM, 2008)

1.3 Research Objectives

This research aims to achieve the following main objectives:

i. Monitoring and modeling the post-seismic motion for Peninsular Malaysia by using 2004 until 2008 data series.
ii. Identifying movements of suspected fault based on the post-seismic motion in Peninsular Malaysia from 2004 until 2008.

1.4 Research Scope

This research covered the following aspects:

i. Theoretical and practical evidence indicated to divide Peninsular Malaysia into western and eastern parts.
ii. GPS processing using the following as the methodology:
    a) GPS data collected from Malaysia Active GPS System (MASS) and Malaysia Real Time Kinematic GNNS Network (MyRTKnet) Stations from all over Malaysia, which was provided by Department Survey and Mapping Malaysia (DSMM). The GPS data used in this thesis from December 2004 until December 2008.
    b) Another set of data from the IGS stations is also used in this study. Thirty IGS stations were used in this study.
    c) The software Bernese 5.0 was used to process the GPS data.
    d) A double difference with Quasi Ionosphere Free (QIF) strategy was used in this study.
    e) All the daily solutions were mapped into ITRF 2005.
iii. Post-seismic modelling
    Post-seismic motion patterns due to Aceh, Nias and Bengkulu earthquake, which observed from 2004 until 2008 was modeled by using a mathematical approach and visualized by using a Generic Mapping Tool (GMT) software.

iv. Identification of fault movement

The best way to monitor the movement of fault is to establish a series of field GPS campaign, on the specific areas of major faults in Peninsular Malaysia. However, there were insufficient funds to do the field measurement but the fault identification used was based on the existing GPS infrastructure in Peninsular Malaysia.

1.5 Research Contributions

Malaysia has an established GPS network that provides high precision positioning in Malaysia, which complies with International standards. The mega thrust earthquakes caused deformation at the GPS stations in Peninsular Malaysia by creating an irregular shape, and also may have caused major faults to be reactivated or formed new minor faults. Therefore, the final results from this study would be an important input for environmental planning, building construction industry and mapping the high risk zone of seismic activity.

1.6 Study Area

The study area of this research covered the regional network around South East Asia and the local network around Peninsular Malaysia, Sabah and Sarawak (Figure 1.3). The largest deformation in Malaysian region caused by the Aceh earthquakes was detected on Peninsular Malaysia. Therefore, the main focus area of this study is Peninsular Malaysia. The specified area of identification fault movement in Peninsular Malaysia was based on the post-seismic result.

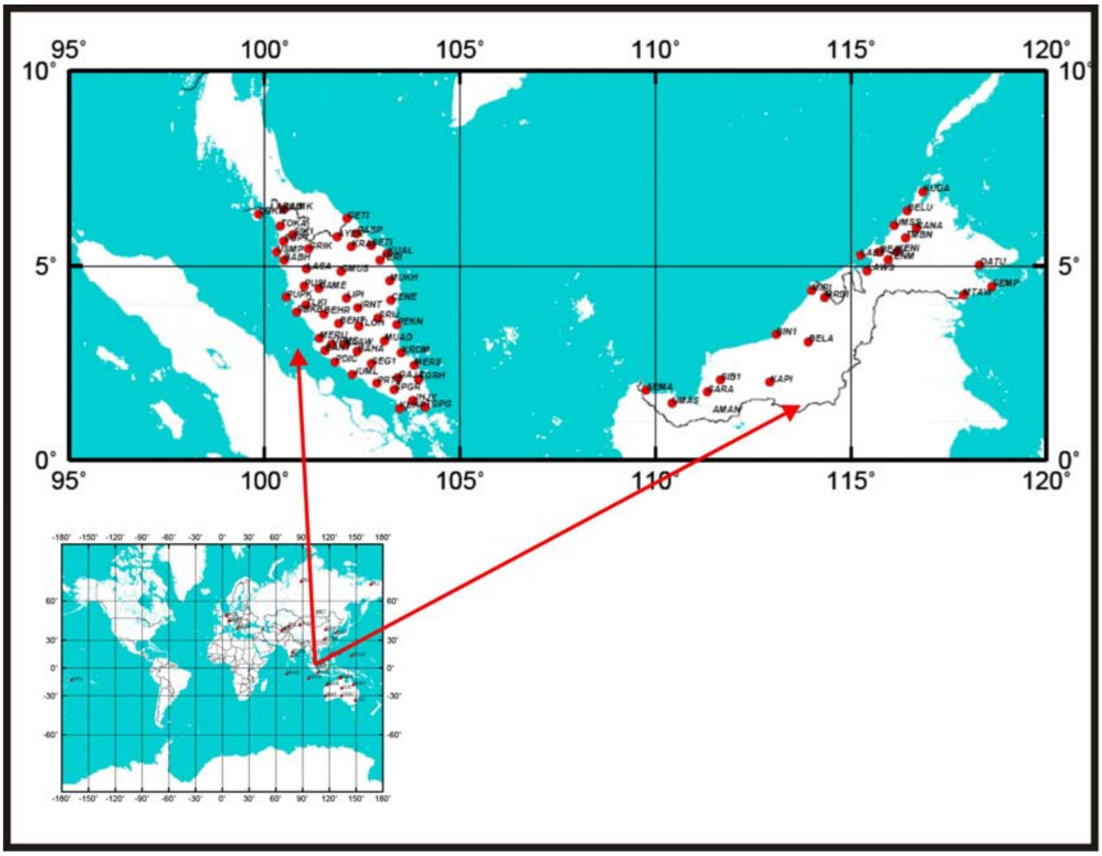

Figure 1.3 Regional and local network

1.7 Research Methodology

The research methodology of this thesis was conducted according to Figure 1.4. Generally, in this study there are three parts. The first part focused on software study and literature review. The second part was data collection and preparation for processing. GPS data from Peninsular Malaysia and East Malaysia was collected from DSMM. Meanwhile the IGS stations' data was downloaded from the IGS website. The third part took into account the GPS data processing and analysis. The results focused on the post-seismic time series and mathematical approach for modelling.

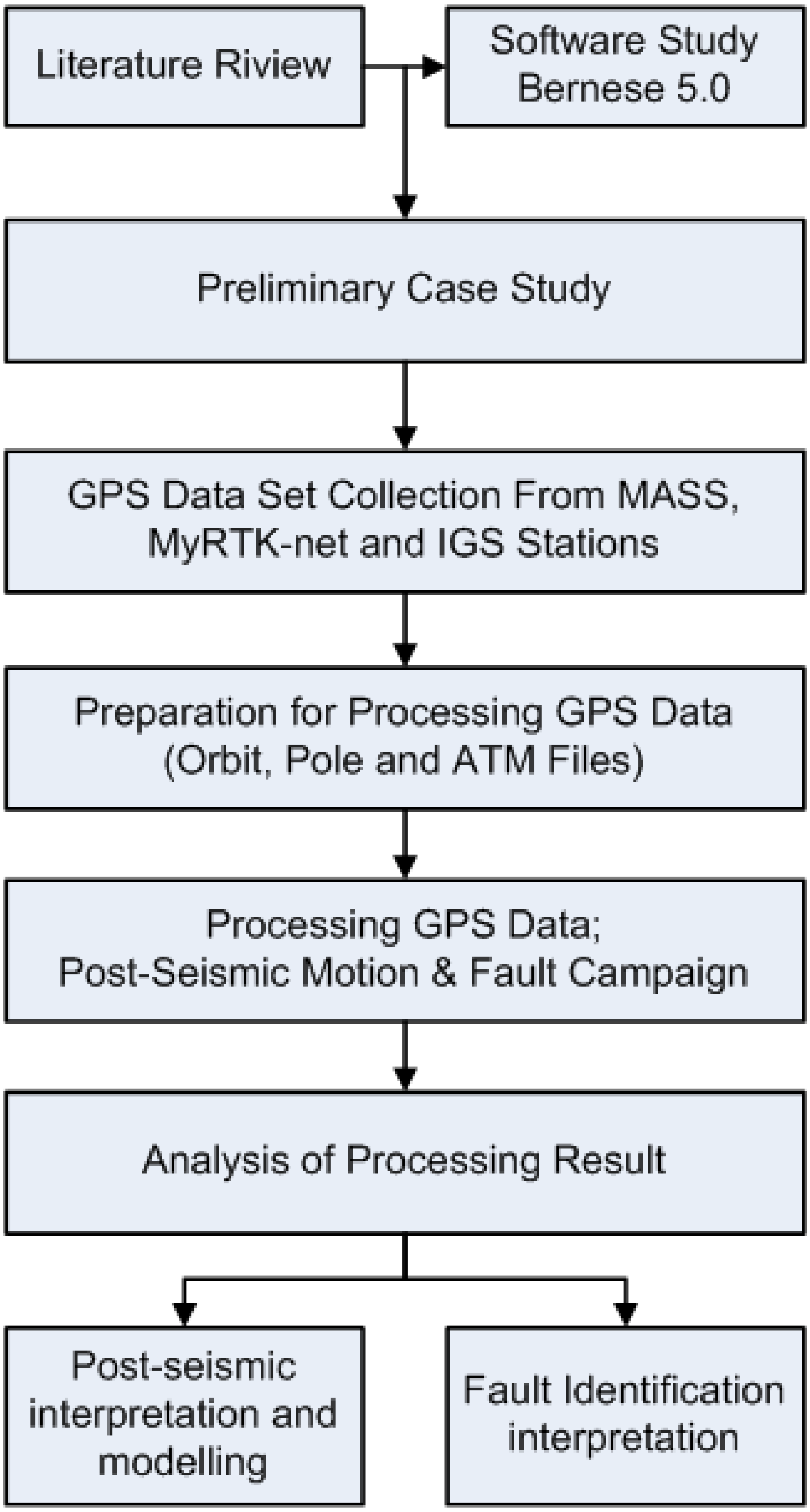

Figure 1.4 Research methodology flowchart

1.8 Chapter Contents

The thesis contains seven chapters. The first chapter consists of the introduction to this research. The second chapter discusses the literature study on the plate tectonic, earthquakes, and tectonic settings of Peninsular Malaysia. The third chapter is about the Global and local GNSS infrastructures and the application to geodynamic studies. The fourth chapter is the data collection and processing strategy. The fifth chapter contains the analysis of the GPS processing results and the interpretation of seismic motions in Peninsular Malaysia. The sixth chapter contains the analysis of the GPS processing results of the fault identification. The seventh chapter is the conclusion inclusive of the recommendation for the improvement of this research in the future. Relevant information that has not been included in the chapters is appended at the end of the thesis.